Comparison of Models for Estimating Yield Loss Caused by Leaf Rust *(Puccinia hordei)* on Zephyr Barley in New Zealand

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ABSTRACT

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The accurate assessment of yield loss is an important component of any comprehensive disease management scheme. Three types of disease-loss models for estimating barley yield loss caused by leaf rust (*Puccinia hordei*) were compared. The critical point, area-under-curve, and multiple point models were evaluated using four selected statistical criteria. Although all models were satisfactory, several multiple point models best predicted yield loss.

Additional key word: Epidemiology.

Leaf rust of barley, caused by *Puccinia hordei* Otth, is a disease that has recently become a concern in both the United Kingdom (9) and New Zealand (1). Control of the disease in New Zealand was expected to require high application of fungicide. To ensure that chemical control would be economically rational, in 1975 we began to develop a disease management scheme (18,19). An essential component is knowledge of the relationship between disease intensity and yield loss. This article reports results characterizing the *P. hordei*/barley yield loss relationship.

James (5) placed models for estimating yield loss caused by plant pathogens in three groups: (i) critical point (CP) models, which estimate yield loss for a given level of disease at a point in the crop's growth or at a given time when a specified level of disease is reached (5,16); (ii) multiple point (MP) models, which estimate yield loss based on sequential disease assessments during a crop's growth (3); and (iii) area-under-curve (AUC) models, which estimate loss from the area under a disease progress curve, measured in arbitrary units (2,22).

All three types of models have been proposed for estimating yield loss caused by cereal rust diseases (2,3,12,16). We used data from field experiments to examine the suitability of the models for describing barley yield loss caused by leaf rust, and this article discusses the value of each model type in relation to its possible use.

MATERIALS AND METHODS

The data needed to examine the relationship between leaf rust and reduction in barley yield were obtained through a field-plot technique with multiple treatments (5). Two trials were conducted during the 1975-76 cropping season and three during 1976-77, with barley cv. Zephyr (20). The randomized block design involved plots 20 × 6 m and four replicates of each treatment. Each trial included untreated plots as well as untreated buffer areas in which naturally occurring epidemics of leaf rust developed. Epidemics of different characteristics and terminal severities were generated by varying the number and timing of application of a systemic fungicide, benodanil (2 iodobenzanilide) at a rate of 0.75 kg a.i./ha. In each

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trial, fungicide was applied to treatment No. 1 at 7–10 day intervals from the onset of disease, to a maximum of six applications. In the same trial the first fungicide application was applied to treatment No. 2, 7–10 days after the first application in treatment No. 1 but coinciding with the second application of treatment No. 1. The other treatments had decreasing numbers of fungicide sprays relative to the first treatment (20). A wider range of epidemics was achieved by sowing each trial at different times in a cropping season.

Rust severity (X_i) was assessed by standard area diagrams based on a percentage scale (6). In all five trials, 10 plants per plot were sampled and the disease severity of all leaves was assessed. Mean disease severities per plot were computed for each leaf position using the FORTRAN program EPICAL. Percentage severity on the two top leaves was used in the disease-loss models for two reasons. First, *P. hordei* epidemics occur late in the season, when leaf 1 (flag) and leaf 2 are the two identifiable leaves that remain free from senescent effects that may interfere with disease asessment. Second, the two top leaves produce most of the carbohydrates in the barley grain (21).

The six growth stages (GS) selected for analyses and labeled according to the decimal code of Zadoks et al (24) were: 39/40, flag leaf ligule/collar just visible; 49/50, first awns to first spikelets visible; 58/59, emergence of inflorescence completed; 64/65, anthesis halfway; 73/74, early milk; and 83/84, early dough. The corresponding points on the Feekes scale (14) are listed in Table 1. The latest was GS 83/84, after which senescence made consistent disease assessment difficult.

Measurements from 10 0.1-m^2 quadrats per replicate plot were used to estimate plot yield. In each trial, the treatment with most sprays was considered to correspsond to the yield of a "disease-free" crop (0% yield loss). This assumption was supported by the observation that mean disease severity on leaf 1 and leaf 2 in this treatment was less than 0.5% in all trials except one, where disease was 3% on leaf 2 (20).

TABLE 1. Designations for independent variables in regression analyses of yield loss caused by barley leaf rust

Independent variable (% leaf rust)	Leaf position	Decimal growth stage[a]	Feekes growth stage[b]
X_1	1 (Flag)	39/40	9
X_2	1 (Flag)	49/50	10.1
X_3	1 (Flag)	58/59	10.5
X_4	1 (Flag)	64/65	10.52
X_5	1 (Flag)	73/74	11.1
X_6	1 (Flag)	83/84	11.2
X_7	2	39/40	9
X_8	2	49/50	10.1
X_9	2	58/59	10.5
X_{10}	2	64/65	10.52
X_{11}	2	73/74	11.1
X_{12}	2	83/84	11.2

[a] From Zadoks et al (24).

[b] From Large (14).

Untransformed and transformed percent rust severities on leaf 1 and leaf 2 at the six growth stages, together with percent yield loss data, were analyzed using a multiple regression package developed by S. J. Filan of the University of New South Wales, Australia. In total, 96 datum-pairs were analyzed. Models were evaluated according to four criteria: (i) r^2 or the coefficient of multiple determination, which indicates the proportion of total variation of the dependent variable (percent yield loss) that is explained by independent variables (rust severity); (ii) F-statistic in the analysis of variance, which tests the overall significance of the regression model at a defined probability level. In all analyses, models were accepted at $P < 0.01$; (iii) s-statistic or standard error of estimate of the dependent variable, which indicates the level of precision associated with the estimation of yield loss from a model; and (iv) t-statistic for each partial regression coefficient, which tests the contribution of each independent (disease) variable to the overall significance of the model.

RESULTS

The independent variables for regression were labeled X_1 to X_{12}, each variable corresponding to rust severity on either leaf 1 or leaf 2 at a specific growth stage (Table 1). Rust severity per tiller was not used as an independent variable because it was considered an inadequate descriptor of the effect of disease on barley yield. Percent yield loss was the dependent variable.

CP models. CP analyses were conducted on the 12 untransformed variables (X_i) and with transformations X^2, X^3, and $X^{1/2}$. The untransformed-variable regressions are in Table 2, which shows that when disease was assessed on leaf 1 (flag), the critical points of assessment were with variables X_3 (GS 58/59) and X_6 (GS 83/84); in these two models, the respective 73.4 and 70.8% of total variation in yield loss was explained by variations in disease. When leaf 2 was assessed, then X_9 and X_{12}, representing GS 58/59 and 83/84, respectively, were the most accurate predictors of yield loss.

These four CP models based on untransformed single leaf assessments, can be expressed as percent yield loss (YL) = intercept + regression coefficient × independent variable, as follows:

$$\% \text{ YL} = 4.69 + 9.69\ X_3 \qquad \text{model 1}$$
$$\% \text{ YL} = 4.78 + 0.31\ X_6 \qquad \text{model 2}$$
$$\% \text{ YL} = 5.30 + 1.81\ X_9 \qquad \text{model 3}$$
$$\% \text{ YL} = 3.19 + 0.27\ X_{12} \qquad \text{model 4}$$

The X^2 and X^3 transformation of disease severity did not produce any improvement in model fit as evaluated by the criteria defined earlier. After square root transformation ($X^{1/2}$), however, several

TABLE 2. Critical point models for yield loss caused by barley leaf rust (single-leaf disease assessments)

Independent variable[a]	Intercept	Regression coefficient	*t*-test	Standard error of dependent variable	F-statistic	r^2
X_1	12.70	1755.87	0.95	13.131	0.89NS[b]	0.039
X_2	11.79	48.61	3.65	10.573	13.31	0.377
X_3	4.69	9.69	7.79	6.909	60.69	0.734
X_4	11.53	0.77	2.94	11.345	8.67	0.283
X_5	9.29	0.53	4.27	9.905	18.23	0.453
X_6	4.78	0.31	7.31	7.235	53.41	0.708
X_7	11.66	6.35	2.86	11.439	8.17	0.271
X_8	10.78	3.26	3.44	10.803	11.83	0.350
X_9	5.30	1.81	8.34	6.566	69.56	0.760
X_{10}	7.86	0.51	5.53	8.668	30.54	0.581
X_{11}	7.05	0.35	6.02	8.235	36.20	0.622
X_{12}	3.19	0.27	7.44	7.141	55.41	0.716

[a] See Table 1 for description.

[b] NS = not significant at $P = 0.01$.

models were better predictors than the above four. The model with flag leaf assessments,

$$\% \text{ YL} = 3.29 \text{ X}_6^{1/2} - 0.10 \qquad \text{model 5}$$

explained 81.1% of total variation, compared with the 70.8% explained by model 2. When leaf 2 disease severities were transformed to square root variables, four models showed improvement relative to untransformed data. These models are as follows:

$$\% \text{ YL} = 0.21 + 8.03 \text{ X}_9^{1/2} \qquad \text{model 6}$$
$$\% \text{ YL} = 1.59 + 4.62 \text{ X}_{10}^{1/2} \qquad \text{model 7}$$
$$\% \text{ YL} = 0.77 + 3.81 \text{ X}_{11}^{1/2} \qquad \text{model 8}$$
$$\% \text{ YL} = -0.43 + 2.90 \text{ X}_{12}^{1/2} \qquad \text{model 9}$$

Models 6–9 explained 80.9, 77.6, 78.5, and 74.2%, respectively, of the total variation in yield loss due to disease. Of these nine CP models, model 5 had the best predictive ability and a standard error of estimate of yield loss of ± 5.82%. In all regressions discussed so far, disease severity at GS 39/40 (X_1 and X_7) and 49/50 (X_2 and X_8) gave poor estimates of yield loss, and these were omitted from subsequent analyses.

A CP model implies that yield loss can be estimated from disease assessment at one growth stage. The above nine models were satisfactory predictors, but all made use of percent severity either on leaf 1 or on leaf 2 at each of these points in a crops's growth. Therefore, assessments on more than one leaf at any given growth stage could be expected to give a better estimate of yield loss. To test this hypothesis, untransformed disease data from two leaves measured at the same GS were regressed with percent yield loss (Table 3). At GS 58/59, two-leaf assessments gave the model:

$$\% \text{ YL} = 4.37 + 4.53 \text{ X}_3 + 1.08 \text{ X}_9 \qquad \text{model 10}$$

This explained 79.6% of total variation and compared very favorably with models 1 and 3, the corresponding individual leaf assessment models at the same growth stage. Similarly, the two-leaf model of GS 83/84,

$$\% \text{ YL} = 3.58 + 0.14 \text{ X}_6 + 0.15 \text{ X}_{12} \qquad \text{model 11}$$

explained 73.3% of total variation in yield loss, which was an improvement on corresponding single leaf models 2 and 4. Improvements in model fit were also similar with two-leaf assessments at GS 64/65 (X_4 and X_{10}) and 73/74 (X_5 and X_{11}).

CP models have been reported for other rust diseases on cereals. According to Romig and Calpouzos (16), yield losses from stem rust of wheat were best predicted from disease severity (S) at the three-quarter berry stage (about GS 85/86 or Feekes 11.2) by the relationship $\% \text{ YL} = 27.17 \log_e X - 25.53$, where X = % S per stem. Keed and White (8) reported that for assessments of the same rust, percent yield loss was equal to 10 times the square root of disease severity at Feekes 11.1 (GS 73/74). With rusts on cereal leaves, wheat yellow rust for example, Doling and Doodson (4) estimated losses from $\% \text{ YL} = 3 \text{ R}^{1/2}$, where R = % S on foliage at flowering. King (10) used a single tiller method for the same rust and found that the average yield loss was approximately equal to 0.3% S on flag at GS 75 (Feekes 11.1). With barley leaf rust caused by *P. hordei*, King and Polley (11) derived CP models of $\% \text{ YL} = 0.6 \text{ S}_1$ and $\% \text{ YL} = 0.4 \text{ S}_2$, where S_1 and S_2 are % S on leaf 1 and leaf 2, respectively, at GS 73/74 (Feekes 11.1). The latter authors estimated the yield loss factors of 0.6 and 0.4 from the average of the regression coefficients of the linear regressions of yield on disease.

With the same method used by King and Polley (11) to estimate a yield loss factor for barley leaf rust, Melville and Griffin (15) found that % YL = 0.77 S, where S was disease severity on leaf 2 at GS 75 (Feekes 11.1). In our analyses, we used yield loss (% YL) as the dependent variable rather than actual yield because the statistical significance of a yield loss factor derived from actual yields is impossible to test (11,15). The models developed for the United Kingdom (11,15) can be compared with CP models 12 and 13 and those listed in Table 1 because they are based on similar growth stages.

$$\% \text{ YL} = 9.29 + 0.53 \text{ X}_5 \qquad \text{model 12}$$
$$\% \text{ YL} = 7.05 + 0.35 \text{ X}_{11} \qquad \text{model 13}$$

Although the F-test was significant for these two models, they explained too little of the total variation in yield loss (45.3 and 62.2%, respectively, Table 2) to be acceptable.

MP models. In one of the first published methods for estimating wheat stem rust losses, Kirby and Archer (13) showed that loss estimates could be improved by making more than one disease assessment during an epidemic. Yet subsequent work to improve models for yield loss estimation in cereals mainly emphasized CP models. The reason is that an MP model usually requires considerably greater labor and cost for data collection than a CP model does (5,6). As shown, even with a CP model, two leaf assessments at a single growth stage are better than one assessment to estimate loss. Results of MP analyses on barley leaf rust are shown in Table 4, with the independent variables X_1 to X_{12} as previously defined. Because variables X_1, X_2, X_7, and X_8 did not produce any significant results in CP analyses, they were omitted from consideration in any MP model. Because a large number of models were formulated by combinations of the remaining eight untransformed variables (X_3 to X_6 and X_9 to X_{12}), only models with a significant F-test explaining more than 90% of total variation in yield loss (r^2) are presented Table 4.

Of the two-growth-stage MP models considered (Table 4), the model that was the best predictor of yield loss was:

$$\% \text{ YL} = 1.54 + 1.18 \text{ X}_9 + 0.16 \text{ X}_{12} \qquad \text{model 14}$$

TABLE 3. Critical point models for yield loss caused by barley leaf rust (two-leaf assessments at one growth stage)

Growth stage[a]	Independent variable	Intercept	Partial regression coefficient	*t*-test	Standard error of dependent variable	F-statistic	r^2
58/59	X_3 X_9	4.37	4.53 1.08	1.95 2.55	6.18	41.14	0.796
63/64	X_4 X_{10}	6.24	−1.32 1.06	−3.39 5.88	7.14	28.26	0.729
73/74	X_5 X_{11}	6.02	−0.77 0.77	−2.36 4.18	7.49	24.64	0.701
83/84	X_6 X_{12}	3.58	0.14 0.15	1.17 1.40	7.08	28.84	0.733

[a] From Zadoks et at (24).

This model explained 92.3% of the total variation in yield loss due to rust and was a considerable improvement over CP models 3 and 4, which predicted yield loss from the disease variables of X_9 and X_{12} and explained 76.0 and 71.6%, respectively, of the variation in loss.

Of the three-growth-stage models, models 15, 16, and 17 were good predictors of yield loss (Table 4). These three models explained a high percentage of the variation in yield loss and all had low standard errors of estimate of yield loss.

When four disease variables were used for regression, three models with high r^2 (models 18, 19, and 20) were obtained. These models explained 93.0, 94.0 and 93.5%, respectively, of the total variation in yield loss due to disease. Model 18 was a two-growth-stage MP model since the variables X_3 and X_9 are for leaves 1 and 2 at GS 58/59 and X_6 and X_{12} are for the two leaves at GS 83/84. Model 20 was based on four growth-stage disease assessments, and with $r^2 = 93.5\%$, was a slightly better predictor than the three-growth-stage models 16 and 17. The variable X_{10} again had a negative partial regression coefficient, as did variables X_3, X_6, and X_{11}. These coefficients were accepted for statistical analysis, but

TABLE 4. Multiple point models for yield loss caused by barley leaf rust

Model number	Independent variable	Intercept	Partial regression coefficient	*t*-test	Standard error of dependent variable	F-statistic	r^2
*[a]	X_3	3.30	1.62	3.60	5.83	47.66	0.819
	X_6		−0.05	−3.15			
14	X_9	1.54	1.18	7.51	3.81	125.64	0.923
	X_{12}		0.16	6.67			
15	X_6	1.47	−0.02	−0.27	3.89	80.08	0.923
	X_9		1.20	7.03			
	X_{12}		0.18	2.95			
16	X_9	1.09	1.42	7.20	3.61	94.28	0.934
	X_{10}		−0.13	−1.83			
	X_{12}		0.19	6.98			
17	X_9	1.13	1.37	7.16	3.67	91.13	0.932
	X_{11}		−0.08	−1.62			
	X_{12}		0.19	6.40			
*	X_3	2.68	4.80	3.37	4.49	34.95	0.880
	X_4		−1.53	−3.04			
	X_5		0.85	2.62			
	X_6		0.15	2.42			
18	X_3	1.30	−2.53	−1.36	3.82	63.05	0.930
	X_6		−0.03	−0.49			
	X_9		1.51	5.30			
	X_{12}		0.22	3.30			
19	X_3	0.98	−2.68	−1.57	3.54	73.93	0.940
	X_9		1.71	6.02			
	X_{11}		−0.09	−1.82			
	X_{12}		0.23	6.35			
20	X_9	1.11	1.44	7.04	3.68	68.16	0.935
	X_{10}		−0.28	−0.94			
	X_{11}		0.11	0.51			
	X_{12}		0.18	5.01			
21	X_3	0.89	−2.13	−1.22	3.51	50.46	0.947
	X_9		1.85	6.10			
	X_5		0.25	1.20			
	X_{11}		−0.31	−1.95			
	X_6		−0.62	−0.70			
	X_{12}		0.20	2.98			
*	X_4	1.81	−2.26	−4.28	4.46	30.25	0.914
	X_{10}		1.36	3.52			
	X_5		0.97	2.17			
	X_{11}		−0.74	−2.38			
	X_6		0.05	0.46			
	X_{12}		0.20	2.56			
22	X_3	−0.07	−4.35	−2.50	2.49	77.62	0.976
	X_9		3.26	5.43			
	X_4		0.72	1.17			
	X_{10}		−1.82	−3.11			
	X_5		0.62	2.12			
	X_{11}		0.42	1.49			
	X_6		−0.03	−0.51			
	X_{12}		0.22	4.61			

[a] * Included for comparison

their biological meaning or interpretation may not be possible. Burleigh et al (3) also included negative coefficients in their MP models for wheat leaf rust.

When disease assessments on two leaves at three growth stages were used to give six variables for regression, only model 21 showed improvement in r^2 when compared with all models considered so far. This model explained 94.7% of the variation in yield loss.

Yield loss in barley, caused by leaf rust, was best estimated by MP model 22 with disease assessments of leaf 1 and leaf 2 at four growth stages. This model explained 97.6% of the variation in yield loss and had the form:

$$\% \text{ YL} = -0.07 - 4.35 X_3 + 3.26 X_9 + 0.72 X_4 - 1.82 X_{10} + 0.62 X_5 + 0.42 X_{11} - 0.03 X_6 + 0.22 X_{12} \qquad \text{model 22}$$

The growth stages, with disease variables on leaf 1 and leaf 2, were 58/59 (X_3, X_9), 64/65 (X_4, X_{10}), 73/74 (X_5, X_{11}), and 83/84 (X_6, X_{12}).

The results in Table 4 confirmed observations by others (3,13) that, although a single disease assessment may be adequate for estimating yield loss caused by cereal rusts, additional assessments will produce better estimates of loss. With the CP models, the growth stages that were important for predicting final yield reduction were 58/59 (X_3, X_9) and 83/84 (X_6, X_{12}). Significantly better predictions were obtained with MP models using these two growth stages and either leaf 1 or leaf 2 disease assessments. Addition of another growth stage for disease assessment further improved the loss estimate, as shown by models 16 and 17. However, the best estimate of yield loss was provided by the model based on assessments of leaf rust on the two topmost leaves at four growth stages (model 22).

AUC models. Disease progress on leaf 1 and 2 in each treatment was plotted using a y-axis scale for disease severity (% S) of 2.54 cm = 10% S and an x-axis scale for time of 2.54 cm = 10 days. The area-under-the-disease-progress-curve, AUC (22), for each leaf treatment was cut out and measured on an automatic area meter. Although the areas were expressed as square centimeters, they do not have any biological or dimensional meaning and should be considered only as arbitrary units for comparative purposes. Percent yield reduction was regressed against untransformed AUC data linearly and the results are in Table 5.

Although 10 of the 12 models in Table 5 were significant in the analysis of variance (at $P = 0.01$), the percent variation in yield loss explained by all 10 models was in the 58.2–74.7% range. The square root transformation of the AUC for leaf 1 gave the best predictor of loss; the model has the form:

$$\% \text{ YL} = 0.10 + 3.21 \text{ AUC}^{1/2} \qquad \text{model 23}$$

Of the two untransformed AUC models, the leaf 1 model explained about twice the percent variation in yield loss of the leaf 2 model (Table 5) and had the form:

$$\% \text{ YL} = 5.05 + 0.30 \text{ AUC} \qquad \text{model 24}$$

with $r^2 = 0.62$.

Vanderplank (22), who proposed the AUC hypothesis, showed a linear relationship between % YL and the untransformed AUC for wheat stem rust, based on data from Kirby and Archer (13) and Kingsolver et al (12). When Romig and Calpouzos (16) attempted to fit an AUC model to their stem rust data, however, the result was inconclusive because of too few observations. When Buchenau (2) linearized his rust progress curves using Vanderplank's logit transformation (22), he demonstrated a good relationship between yield loss and area under the straight line between logits of +5 and −5.

In our study of barley leaf rust, linearization of the disease progress curves was attempted, but the regression coefficients of the logit lines had high standard errors due to the variety of curve shapes in treatments in which epidemics were modified with fungicide. Consequently, only the untransformed curves were used for AUC determination. Using untransformed data, Buchenau (2) found a 1:1 relationship between yield loss and AUC of stem and leaf rust of wheat. With barley leaf rust, model 24 indicates that an increase of 0.3 units of leaf 1 AUC will result in 1% yield loss, with about 8% error in the loss estimate. In a comparison of CP and AUC models for estimating yield loss due to Cercospora leaf spot in cowpea, Schneider et al (17) concluded that James' criteria (5) for a CP model—short and late epidemic—could be equally applied to an AUC model. Barley leaf rust epidemics generally have a short duration and occur late in a crop's growth. It was not surprising therefore that the AUC model 24 was statistically significant.

DISCUSSION

Leaf rust reduced yield in barley mainly by reducing the weight of grain (20). The rust did not affect the final number of tillers reaching maturity, ie, harvestable ears per plant, but this was to be expected because disease was severe only during the later part of the crop's growth (20). Late development of barley leaf rust was also noted in England (11,15), where the disease affected yield by reducing 1,000-grain weight. Yield analyses (20), however, show that the difference in percent reduction of 1,000-grain weight between treatments with low and high rust was consistently less than the overall reduction in yield. This effect has been reported by other workers (7,15) and is attributed to the disproportionate loss of grain from unsprayed (high rust) plots during harvesting and seed cleaning. Although there is consensus that the top part of the cereal tiller (ear and two topmost leaves) is mainly responsible for grain dry matter, the actual contribution of each of the plant parts concerned is still uncertain (21). A late rust epidemic can be expected to reduce weight by imposing constraints on grain filling (dry matter accumulation). One constraint may be source

TABLE 5. Area-under-curve models for yield loss caused by barley leaf rust

Leaf position	Independent variable[a]	Intercept	Partial regression coefficient	*t*-test	Standard error of dependent variable	F-statistic	r^2
1	AUC	5.05	0.298	6.39	7.93	40.78	0.620
1	AUC^2	8.32	0.029	4.67	9.50	21.80	0.498
1	AUC^3	9.64	0.00003	3.92	10.28	15.34	0.411
1	$AUC^{1/2}$	0.10	3.208	8.07	6.73	65.07	0.747
1	$\log_e AUC$	8.70	3.49	5.98	8.27	35.73	0.619
1	0.5 AUC	5.05	0.60	6.39	7.93	40.78	0.649
2	AUC	10.12	0.09	3.12	11.45	9.74	0.307
2	AUC^2	14.15	0.0001	1.32	12.89	1.75NS[b]	0.074
2	AUC^3	14.75	0.2×10^{-6}	0.88	13.16	0.79NS	0.034
2	$AUC^{1/2}$	2.19	2.15	5.55	8.64	30.80	0.583
2	$\log_e AUC$	3.71	4.23	5.54	8.66	30.64	0.582
2	0.5 AUC	10.12	0.18	3.12	11.15	9.74	0.307

[a] AUC = area-under-disease-progress-curve.

[b] NS = not significant at $P = 0.01$.

limitation through reduction in photosynthetic area. Others include fungal metabolism and increased evapotranspiration through pustules (23) that produce water stress.

Three characteristics of barley leaf rust epidemics—late development, reduction in yield due to reduction in grain weight, and short epidemic duration—indicated from the outset that a CP model for estimating yield loss could be fitted to the data. It was therefore not surprising that several CP models satisfied the statistical criteria for model acceptance. An AUC model based on leaf 1 disease assessments satisfactorily explained variation in yield loss, but it was considered inferior to the CP models. MP models were better estimators of barley yield loss due to leaf rust than both CP and AUC models.

The intended use of a model influences selection of the model type. For example, if an estimate of crop loss on a regional scale is desired, and a large number of fields must be examined, then a CP model would be the most practical. When considering disease projections for management (5,18,19), however, the increased precision required of a loss estimate would favor an MP model.

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